# Electrochemical Double Layer Capacitor Modeling and Vehicle Simulations

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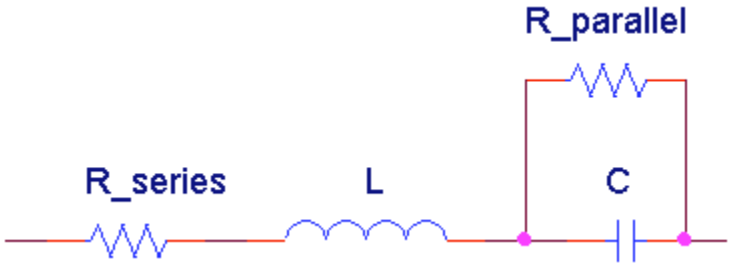
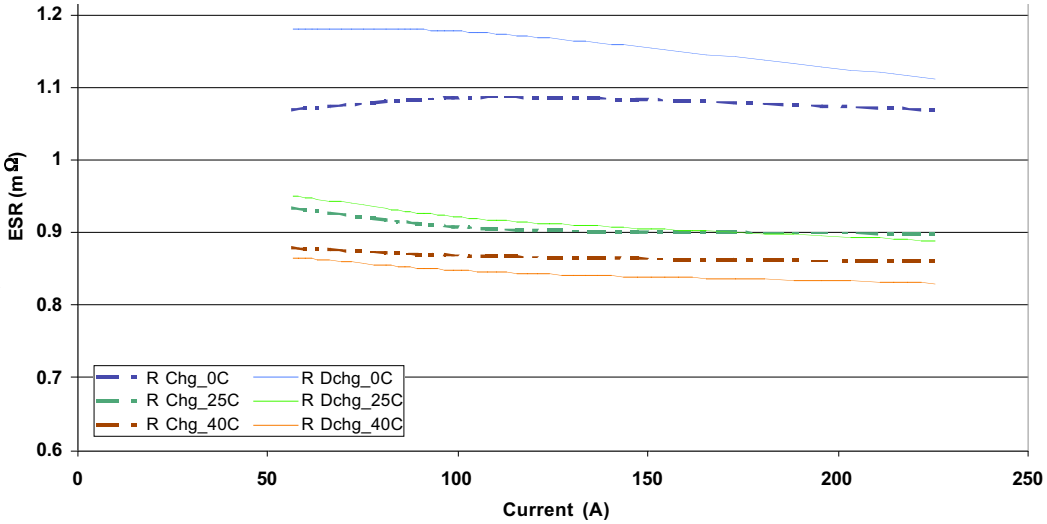
# Outline

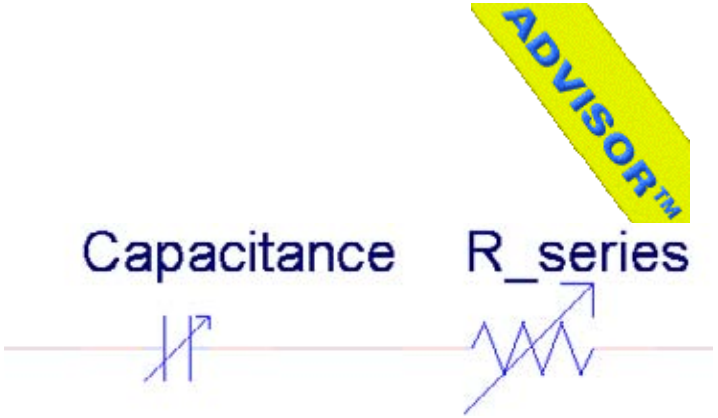
- **Electrochemical Double Layer Capacitor (EDLC) Model**
- Dual-Source Battery/EDLC Testing/Simulations
- Fuel Cell Hybrid Vehicle Simulations
- Points of Discussion

# Equivalent Circuit Capacitor Model for EDLC

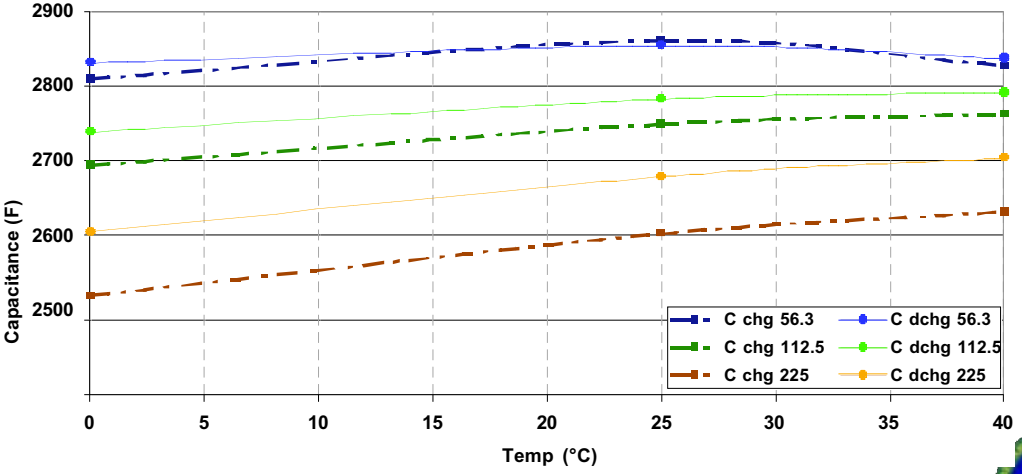



- First-Order Capacitor Circuit Model

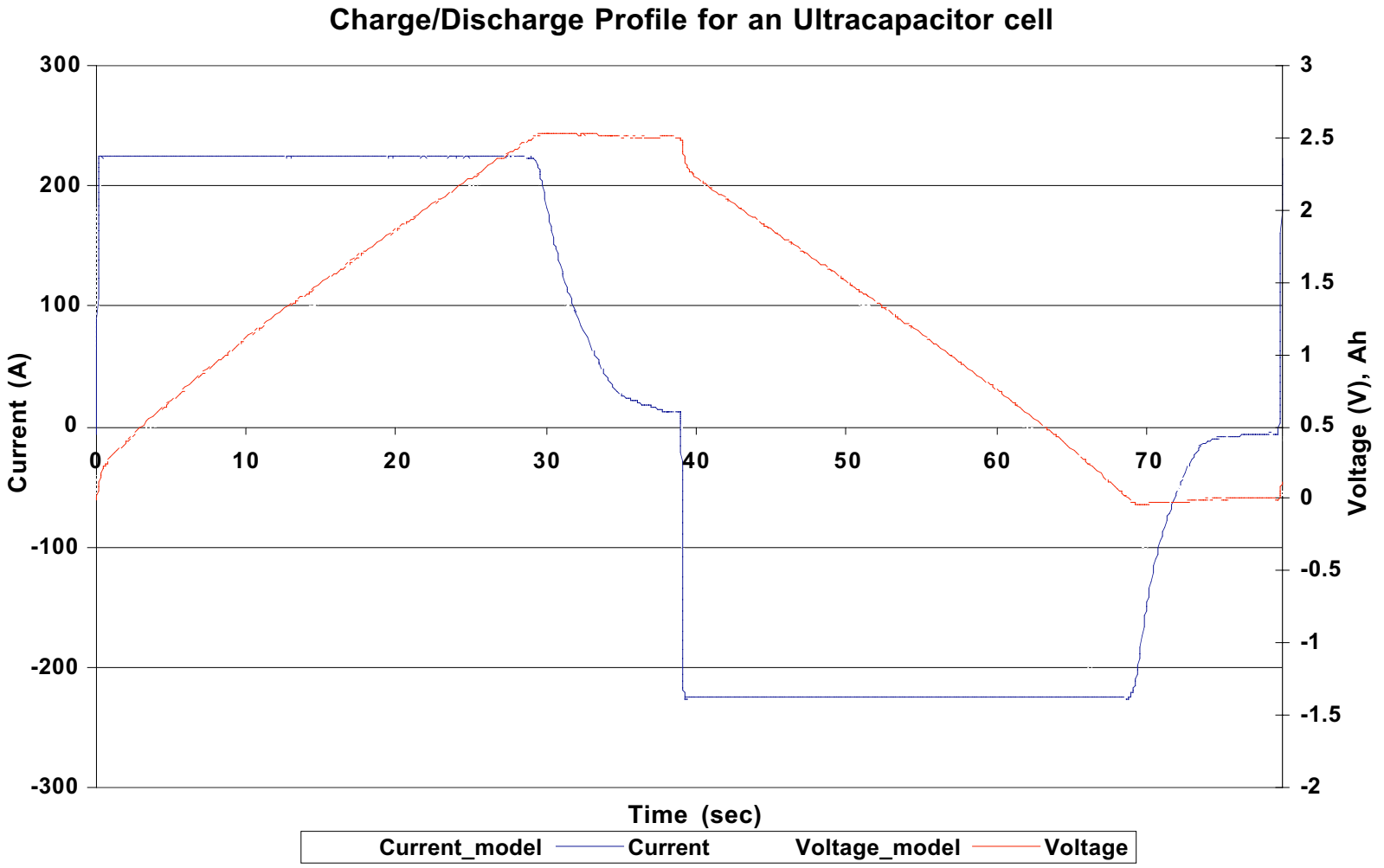



- First-Order model varies with temperature/current parameters



# EDLC Model Compares Well with Lab Data



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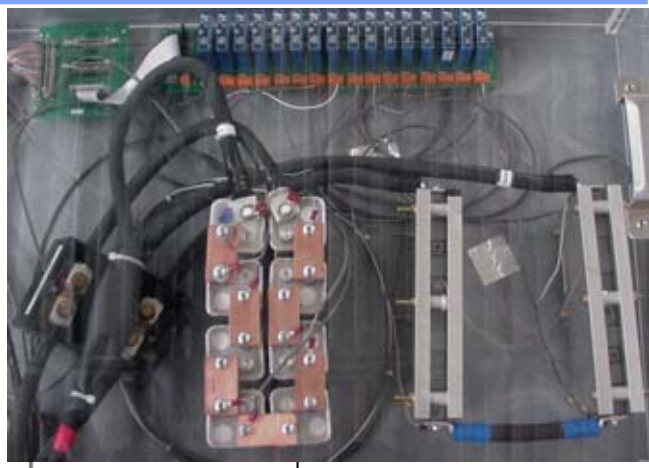
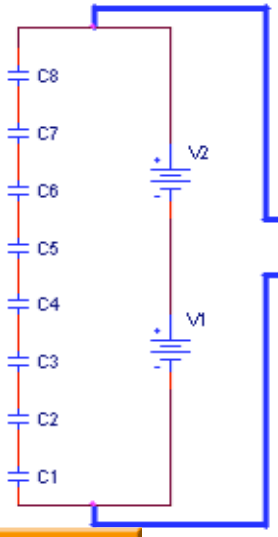
## Case A – Battery-Only Pack



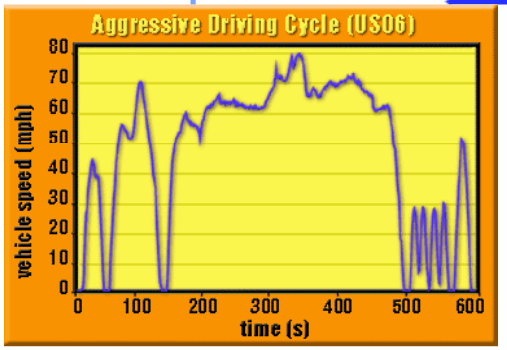

- High power NiMH batteries in the U.S. Prius
- Two 6.5Ah modules at 14.4V nominal (18V max)

## Case B – Simple Hybrid Energy Storage Pack

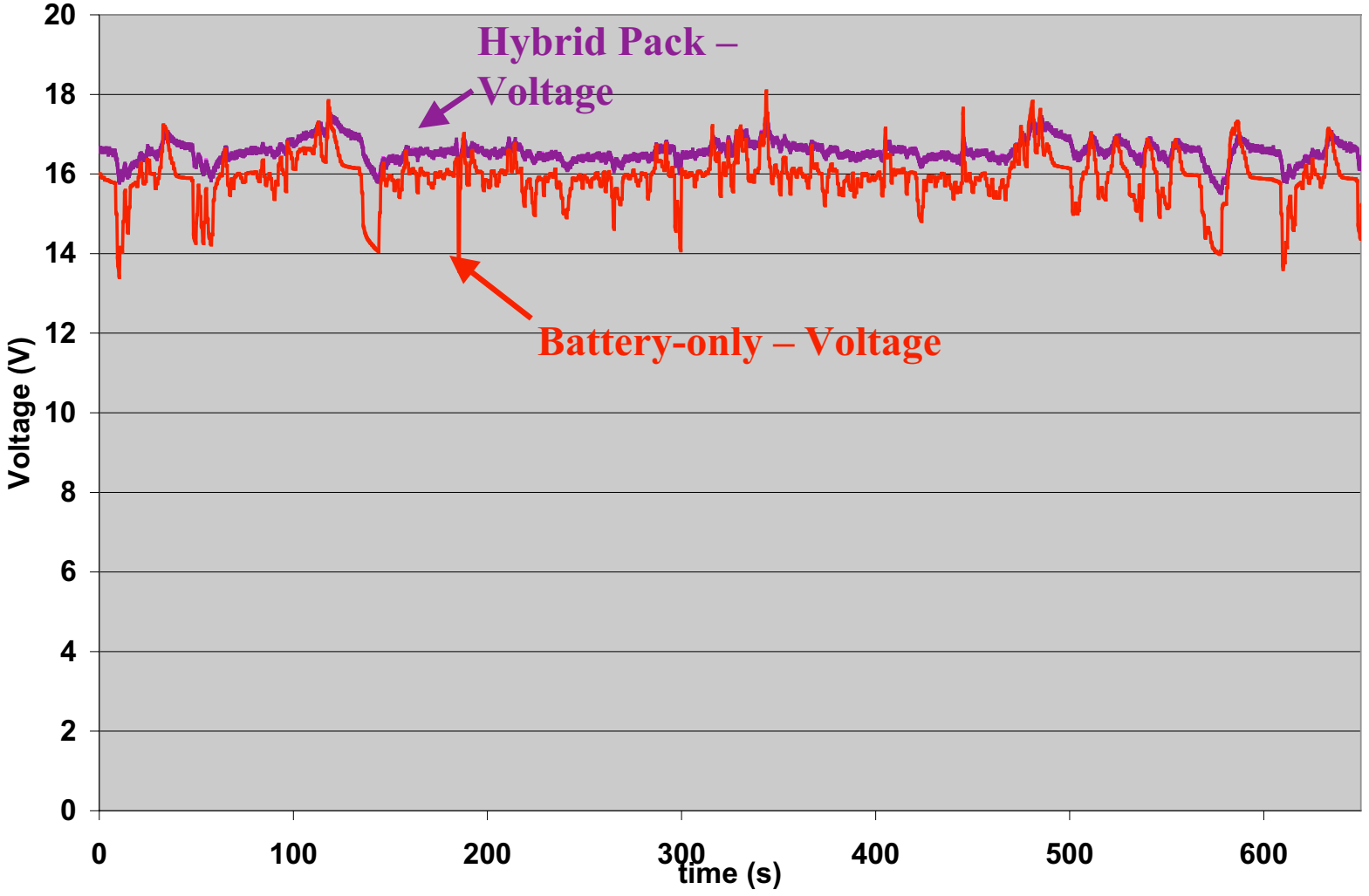




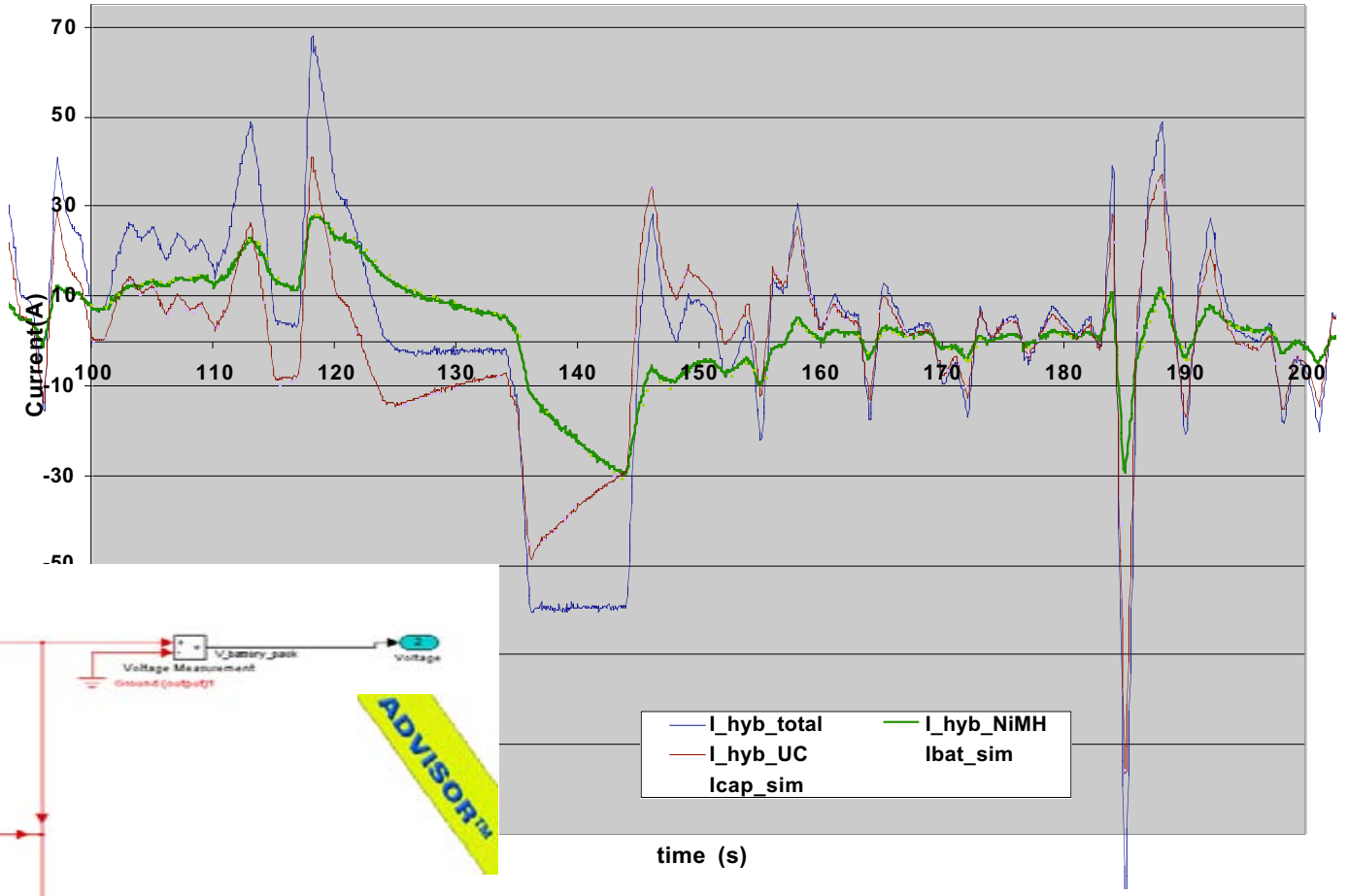

- EDLC module of 8 cells (up to 20V)
- 6.5Ah NiMH stack of 14.4V (18V max).

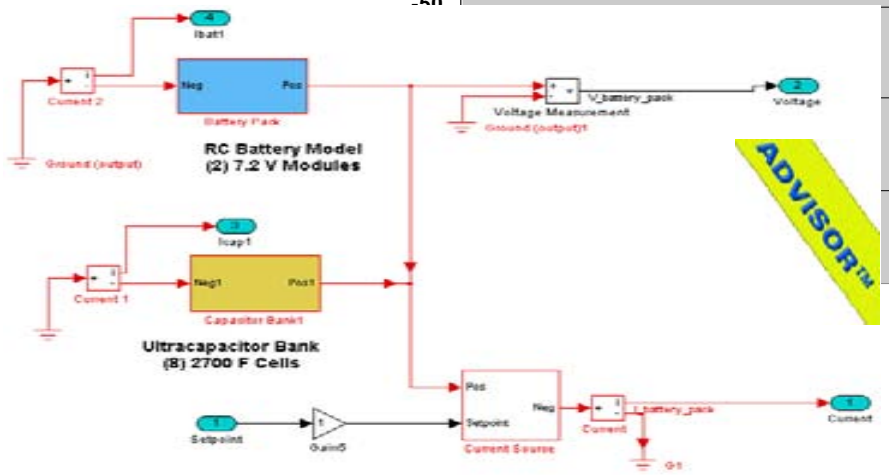


# EDLCs Filter Voltage Transients

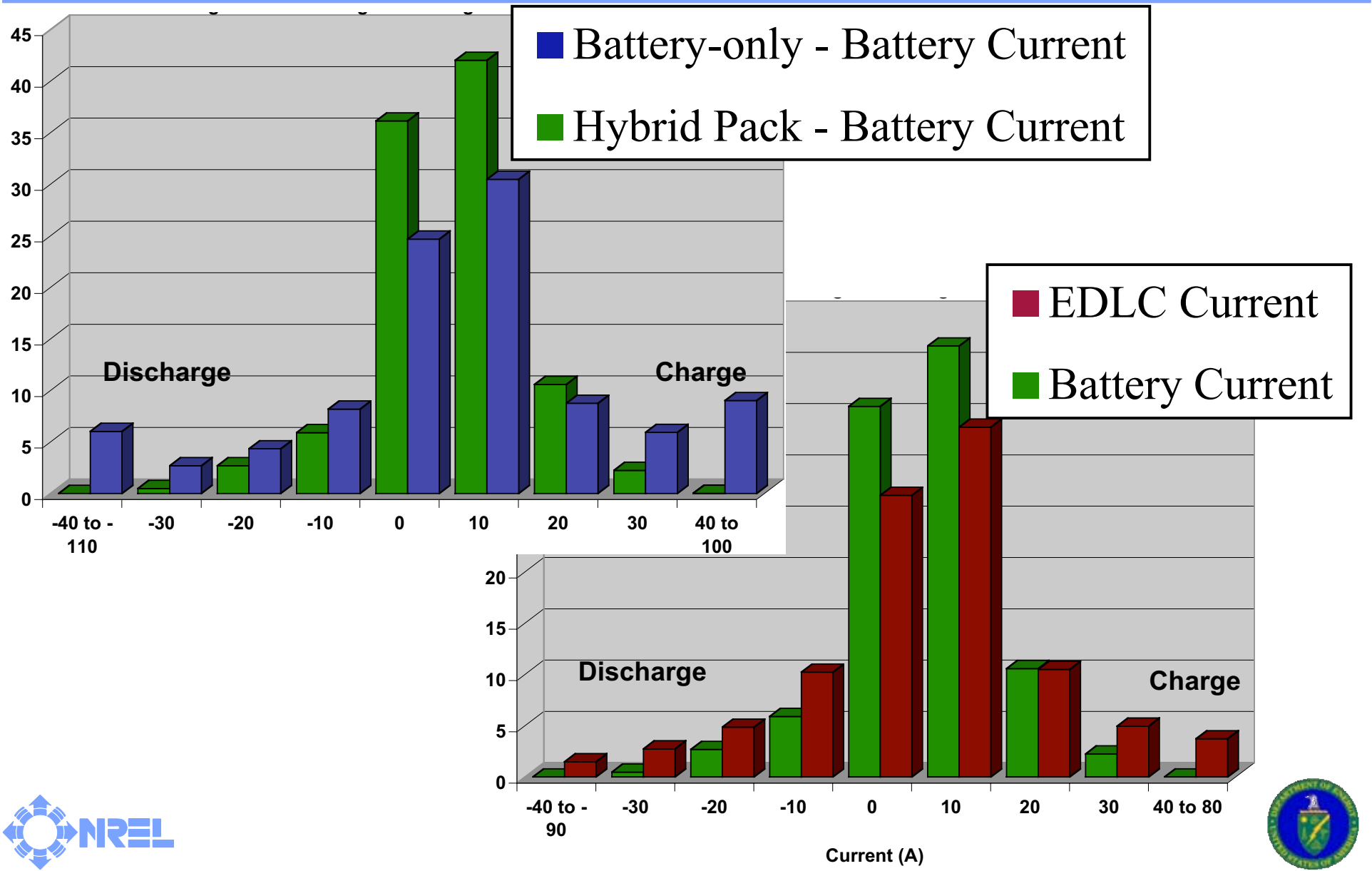


# Battery Currents in the Hybrid-Pack Are Reduced Compared to the Battery-Only Pack

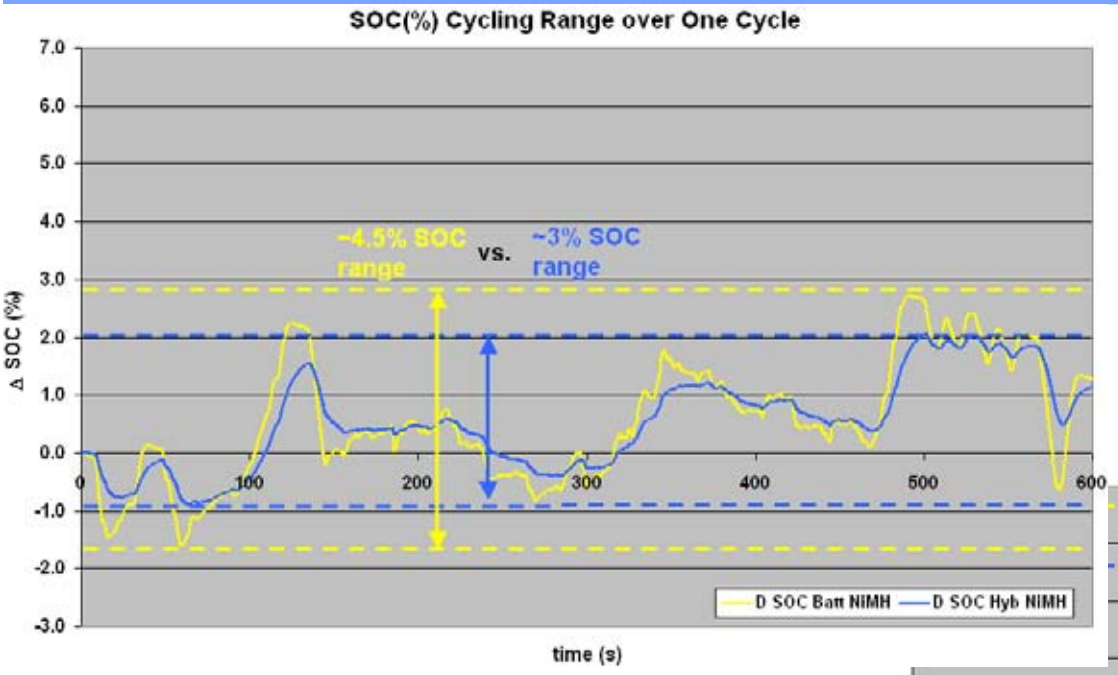


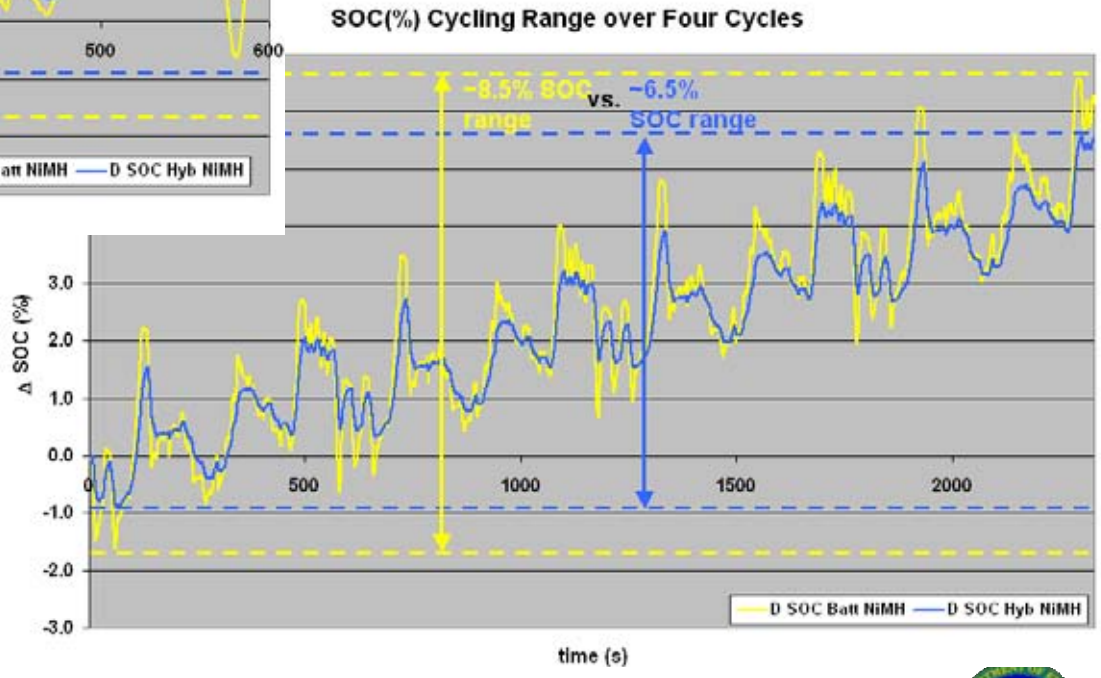



# Current Histogram in the Hybrid Pack and Battery-Only Pack during the US06

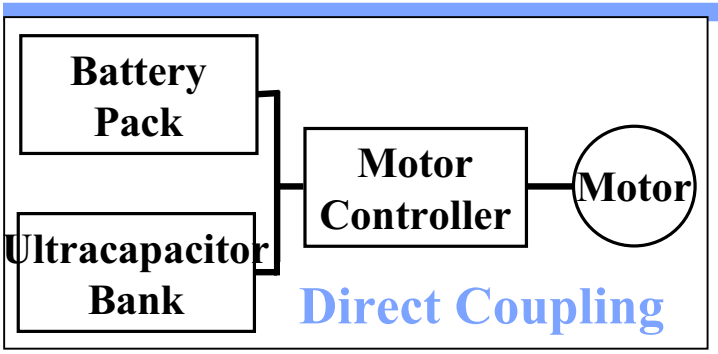


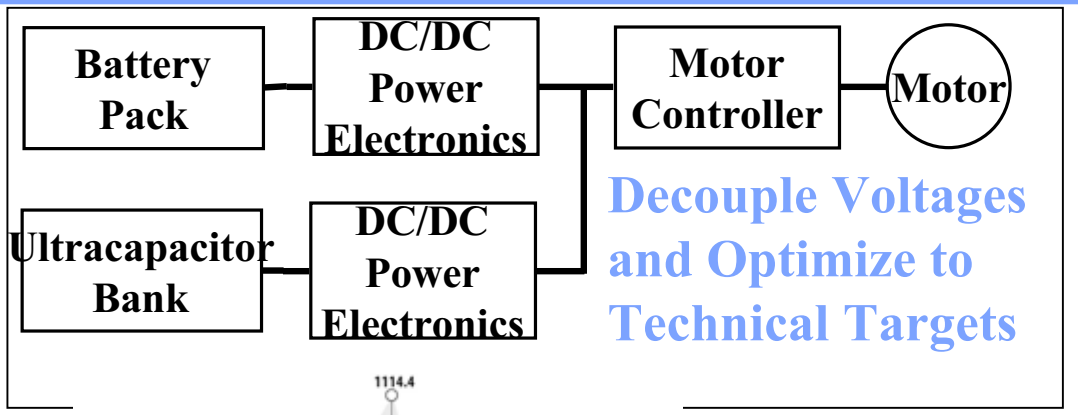
# Narrower Battery SOC Range Over US06 Profile(s) has potential to increase battery life

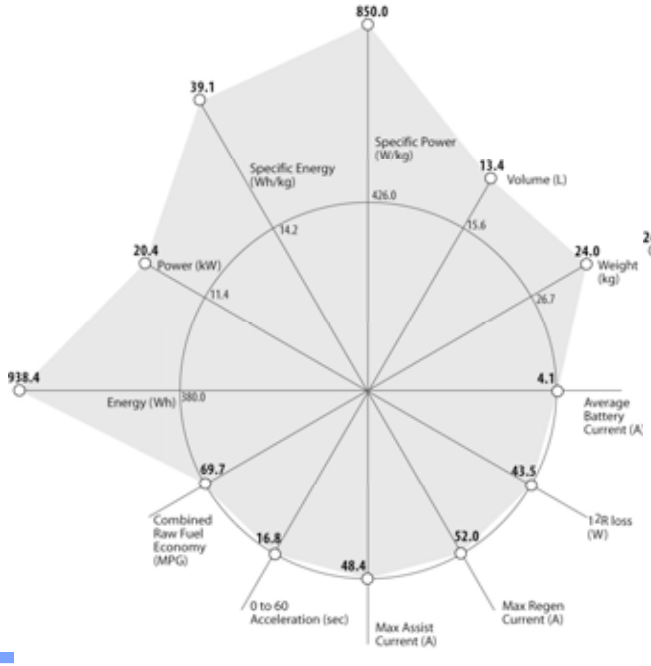


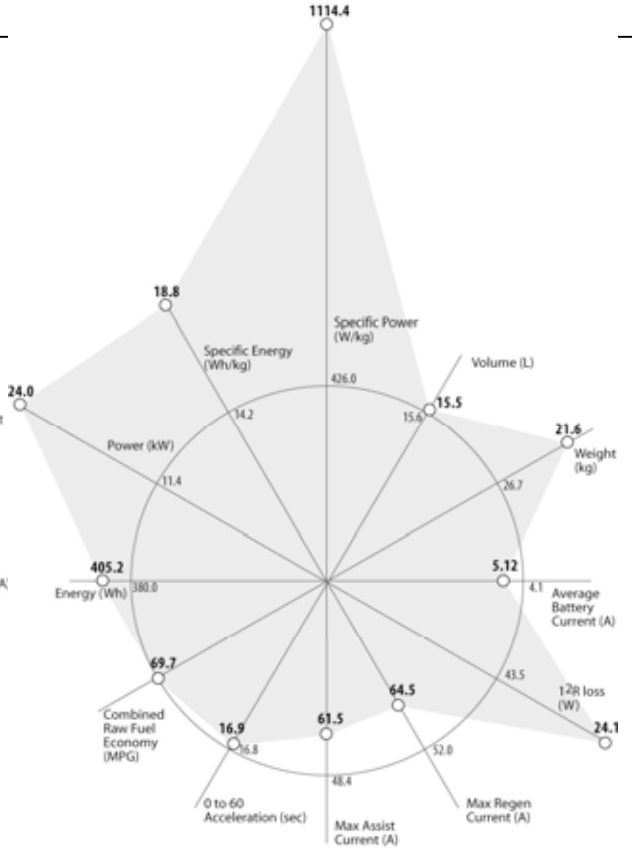



# Dual-Source Coupling Studies



# Control Strategy Development

ICE

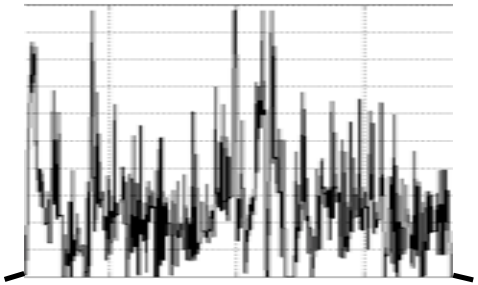
FuelCell Stack

OR

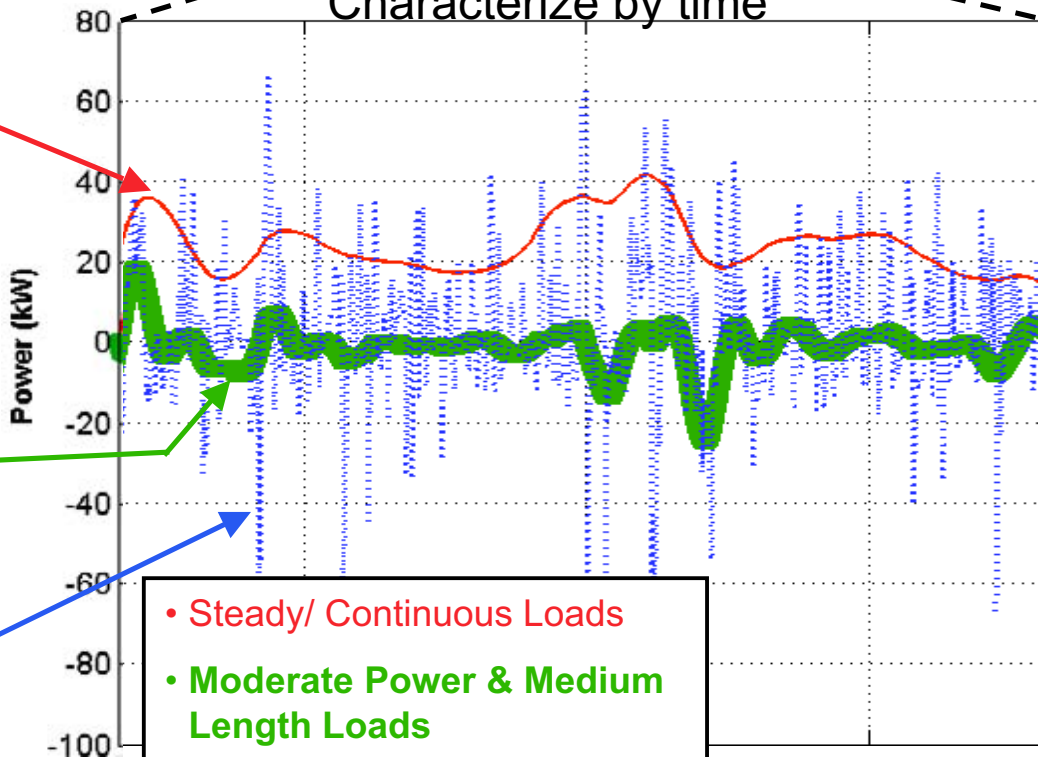
Battery Pack

EDLC Bank

Vehicle Loads



Characterize by time




- Steady/ Continuous Loads
- **Moderate Power & Medium Length Loads**
- Highly Transient, Peak Loads

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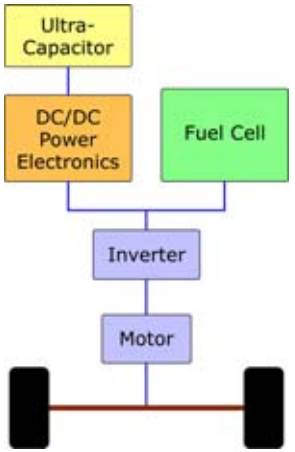
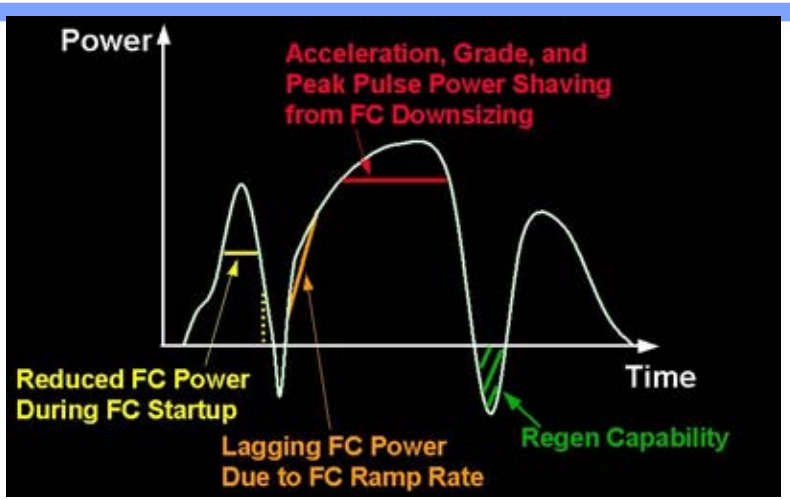
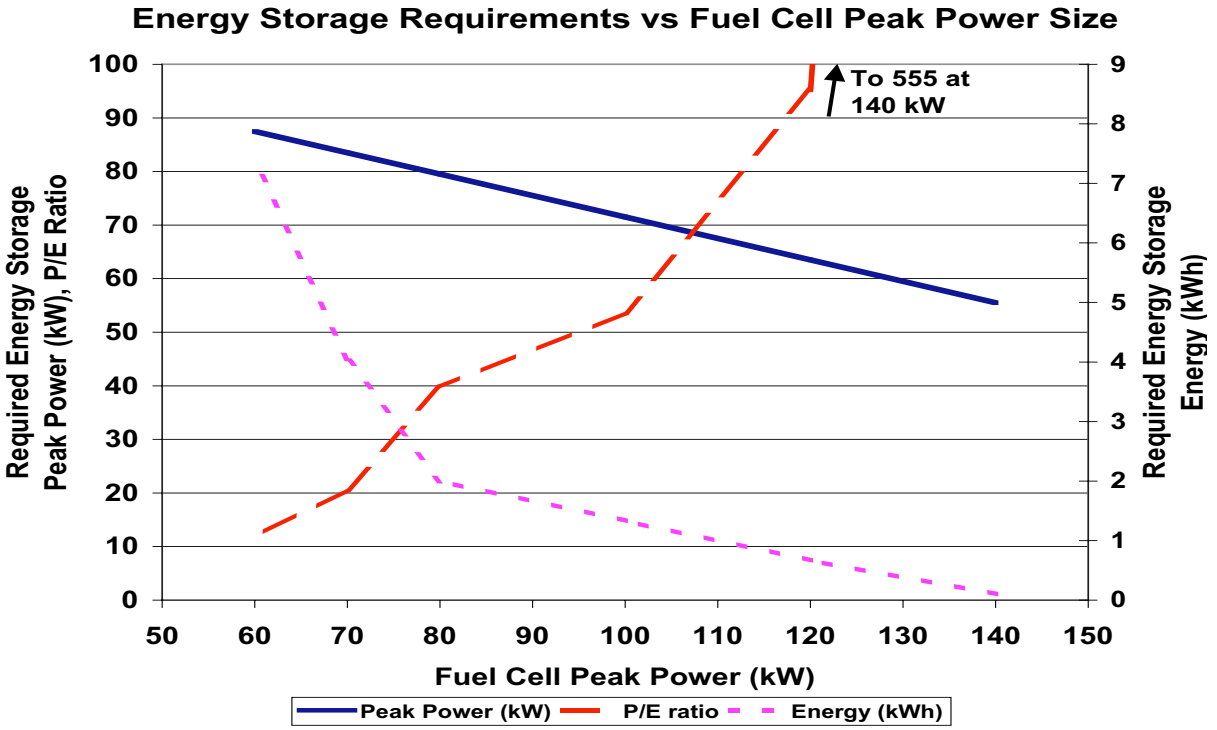
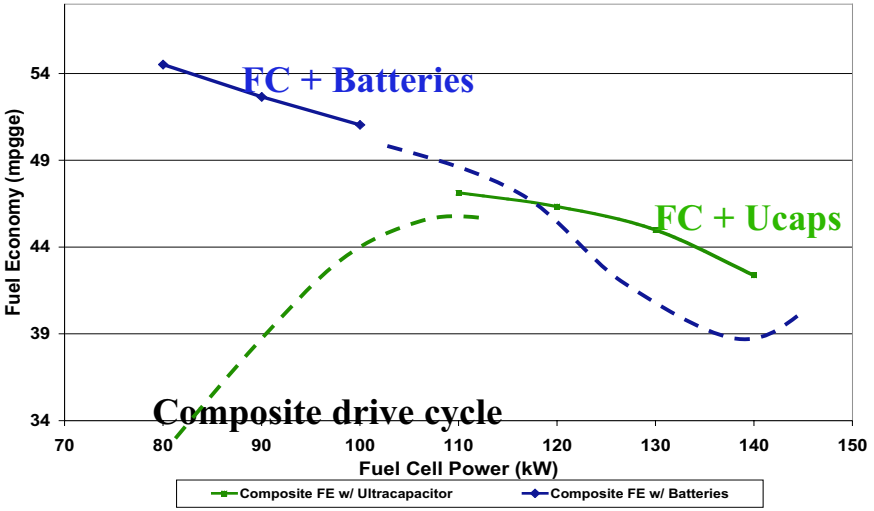
# Fuel Cell Hybrid Vehicle Studies -Roles

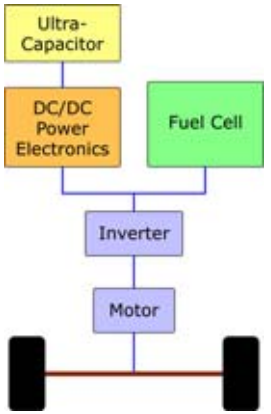


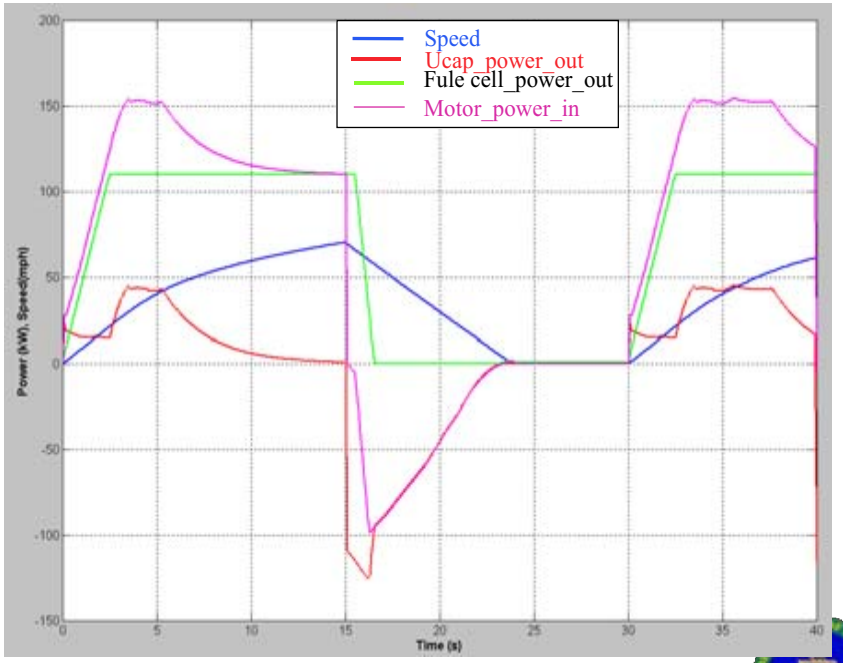



# Fuel Cell Hybrid Vehicle Studies –Battery and EDLC



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# Points of Discussion (page 1 of 2)

- EDLC/Battery life questions:
  - What is relationship of battery life vs. SOC cycle range?
  - What is relationship of battery life vs. maximum current magnitudes?
  - What is the in-use life of EDLC's versus batteries?
- Can tightly coupled control strategy development & energy storage optimization (performance, sizing, cost, life-time) result in advanced solutions?
- Does driveline optimization make sense to extending optimization work (battery/uc → power electronics/motor drive → motor)?

# Points of Discussion (page 2 of 2)

- Fuel Cell hybridization with EDLC's can provide benefit, but how much should the fuel cell be downsized?
- Mild EDLC hybridization strategies need further evaluation/prioritization
  - Regenerative energy recapture
  - Utilized to adjust prime mover operation for maximum efficiency?
  - Traction assist? Transient suppressions?
  - Fill in for fuel cell ramp up?
  - Fuel cell buffer for high frequency harmonics?
  - …
- With 42V system, will EDLC-only, Battery-only, or Dual-Source system provide most benefit?

# List of Publications

- M. Zolot, M. Mihalic, A. Pesaran; "*UltraCapacitor Testing, Modeling, and Hybrid Energy Storage Configurations*" 2001 DOE Milestone.
- M. Zolot, B. Kramer, M. Mihalic; "*Battery and Ultracapacitor Simulation and Optimization for FreedomCAR Technologies*" 2002 DOE Milestone.
- M. Zolot, B. Kramer; "*Hybrid Energy Storage Studies Using Batteries and Ultracapacitors for Advanced Vehicles*" Presented to the 12th International Seminar on Double Layer Capacitors and Similar Energy Storage Devices; December 9-11th, 2002, Deerfield Beach, Florida.
- T. Markel, M. Zolot, K. Wipke, A. Pesaran; "*Energy Storage System Requirements for Hybrid Fuel Cell Vehicles*" Advanced Automotive Battery Conference; June 10-13th, 2003, Nice, France.
- R. Schupbach, J. Balda, M. Zolot, B. Kramer; "*Design Methodology of a Combined Battery-Ultracapacitor Energy Storage Unit for Vehicle Power Management*" IEEE 2003 Power Electronics Specialists Conference (PESC); June 16th, 2003, Acapulco, Mexico.
- M. Zolot; "*Dual-Source Energy Storage – Control and Performance Advantages in Advanced Vehicles*" EVS-20 Conference; November 15-19th, 2003, Long Beach, California.